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Giant submarine canyons:
Is size any clue to their importance in the rock record?

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ABSTRACT

Submarine canyons are the most important conduits for funneling sediment from continents to oceans. Submarine canyons, however, are zones of sediment bypassing, and little sediment accumulates in the canyon until it ceases to be an active conduit. To understand the potential importance in the rock record of any given submarine canyon, it is necessary to understand sediment-transport processes in, as well as knowledge of, deep-sea turbidite and related deposits that moved through the canyons.
There is no straightforward correlation between the final volume of the sedimentary deposits and size of the associated submarine canyons. Comparison of selected modern submarine canyons together with their deposits emphasizes the wide range of scale differences between canyons and their impact on the rock record.
Three of the largest submarine canyons in the world are incised into the Beringian (North American) margin of the Bering Sea. Zhemchug Canyon has the largest cross-section at the shelf break and greatest volume of incision of slope and shelf. The Bering Canyon, which is farther south in the Bering Sea, is first in length and total area. In contrast, the largest submarine fans—e.g., Bengal, Indus, and Amazon—have substantially smaller, delta-front submarine canyons that feed them; their submarine drainage areas are one-third to less than one-tenth the area of Bering Canyon. Some very large deep-sea channels and turbidite deposits are not even associated with a significant submarine canyon; examples include Horizon Channel in the

northeast Pacific and Laurentian Fan Valley in the North Atlantic. Available data suggest that the size of turbidity currents (as determined by volume of sediment transported to the basins) is also not a reliable indicator of submarine canyon size.

INTRODUCTION

Submarine canyons continued to be a major area of interest for Francis P. Shepard throughout his career. His Submarine Geology textbooks, which were revised over the years, devoted substantial space to a review of the world's canyons that were known at the time; these reviews were a standard resource for several decades of marine geologists (e.g., Shepard, 1973). Shepard and his coworkers observed that canyon size was not directly related to the size of the rivers that fed them. In fact, many major canyons were not fed directly from rivers but fed from littoral drift transport of beach sediment, for example, the La Jolla Canyon (Shepard, 1973; Shepard and Dill, 1966). As our ability to map the deep-sea floor has improved since Shepard's pioneering work, it has become clear that the size of submarine canyons also shows no simple relation to the size of the turbidite systems—- submarine fans, abyssal plains, slope basin deposits, etc.—- fed through the canyons.

In this review, we accept the characteristics of submarine canyon presented by Shepard (1963) to distinguish canyons from the channels that form their seaward extension. Canyons are cut into shelf and slope bedrock and sediment, typically have a V-shaped profile, and have a steeper gradient than the channels formed in the depositional areas associated with the canyons. Canyons lack levee morphology commonly found along channels extending from mouths of the canyons. Shepard (1973) did distinguish delta-front troughs, which are "closely related to submarine canyons." For the sake of brevity, we use the term canyon for both types of features in this review.

Before declaring the "world's largest submarine canyon," we need to consider what criteria should be used to define largest. Should the criteria be the maximum submarine "drainage" area, the largest cross section, the maximum volume, or the greatest length? Just based on these four characteristics, Table 1 shows that there are several candidates for "largest canyon."

Because submarine canyons are bypass zones in the transport of sediment from continents to the oceans, one must look at the deposits in the adjacent basins to understand the importance of a submarine canyon. As a consequence, this review will compare a limited number of candidates for largest canyon (together with a few of the smaller, but perhaps more thoroughly studied canyons) and will also consider the size of the associated deposits. It is also instructive to look at those canyon systems that have delivered the greatest volume of terrigenous sediment to the oceans. The examples of smaller canyons selected for inclusion in this review reinforce the importance of physical-scale considerations and emphasize that the rock record is much better represented by the small canyons and their deposits rather than the giant canyons.

LARGEST SUBMARINE CANYON AND LARGEST SUBMARINE FAN

The areas shown in Figure 1 encompass the submarine canyon and the area of its associated deposit(s). The drainage areas of the canyons are given in Table 1, and the cross-sections of these canyons or their major fan valleys are compared in Figure 2. It can by seen that large canyons feeding turbidite systems on the deep ocean floor are typically about 1 km deep in profiles across the canyon near the shelf break. The Zhemchug Canyon, which is twice as deep as the other large canyons depicted, is equaled in width only by Navarin Canyon, which has less than half of the vertical relief of Zhemchug. The La Jolla Canyon, which empties into a small borderland basin on the continental margin, is less than 300 m deep; its size is typical for canyons that feed small basins within continental margin settings. To help visualize the immense size of large submarine canyons, Figure 2 includes a section across the Grand Canyon of the Colorado River in the southwestern United States. The Grand Canyon is deeper than all of the submarine canyons depicted except for the Zhemchug; in cross-sectional area, however, the Grand Canyon is nearly an order of magnitude smaller than the Zhemchug Canyon and falls in the middle of the range of canyons shown in Figure 2. The Swatch of No Ground, which is the equivalent of a submarine canyon on the delta of the Ganges-Brahmaputra Rivers, is only about a tenth of the cross-sectional area of the Zhemchug Canyon (Fig. 2). The Swatch of No Ground, however, feeds the Bengal Fan, which is the largest submarine fan in the ocean (Emmel and Curray, 1985). The size of a submarine canyon is, thus, not a reliable indicator of the volume of sediment that has moved through the conduit.

Using the characteristics given in Table 1, we will review the best candidates for largest submarine canyon, which are all from the Bering Sea margin (Figs. 1 and 2). We then consider the relation of canyon size relative to their associated turbidite deposits.

Zhemchug Canyon

The three largest submarine canyons, based on drainage area (Table 1) and cross-sectional area (Fig. 2), are all from the North American margin of the Bering Sea; Zhemchug Canyon is the largest of these canyons (Carlson and Karl, 1988). Zhemchug Canyon has a volume of at least 5800 km^3, nearly double the volume of the Swatch of No Ground, which is 2950 km^3 (see Table 1 in Carlson and Karl, 1988) and feeds the largest submarine fan, the Bengal.

Zhemchug Canyon, named for the Soviet expeditionary vessel Zhemchug, has two main branches, and each is larger than typical continental-margin canyons such as the Monterey (Fig. 2). A strong case might be made for each branch of the Zhemchug Canyon being separate canyons because both thalwegs traverse the entire slope before merging on the upper rise (Fig. 3; Carlson and Karl, 1988). These two branches occupy a 160-km-long, 30-km-wide, steep-walled trench that is incised into the shelf and oriented northwest-southeast, roughly parallel to the shelf-slope break. The canyon breaches an outer shelf structural high named Pribilof Ridge by Marlow et al. (1976). The canyon, at the regional shelf break, has cut a gorge 100 km wide and 2600 m deep (Figs. 3 and 4). The axial profiles of both branches steepen in a step-like fashion. Transverse profiles of the canyon are steep walled and V-shaped landward of the shelf break. Seaward of the shelf break, the walls are still steep and have great relief (2550 m), but the floor becomes flat and is as much as 10 km wide.

Of all the processes that have been instrumental in shaping the large submarine canyons of the Beringian margin, mass movement has been by far the most important agent, followed by density flows (Carlson et al., 1991). The imprint of tectonism controlled or influenced the locations of the canyons, and glacio-eustatic sea-level changes regulated the timing during which the canyon-cutting processes were most effective. Zhemchug Canyon has breached a structural basin that underlies the Bering shelf. The canyon is eroding into the basin fill, and the shape of the basins and bounding faults (Scholl et al., 1970) control the configuration of the developing canyon heads. The epicenter of a recent earthquake (Abers et al., 1993) is adjacent to the northwest branch of the canyon, which underscores the structural aspect of its formation.

Evidence of mass wasting of sediment in the Beringian margin canyons has been recognized from seismic-reflection profiles (Scholl et al., 1970, Carlson and Karl, 1984–1985; 1988). The GLORIA images collected in 1986 reveal that products of mass wasting are much more common than previously interpreted and that mass wasting is the dominant erosional process on the Beringian continental slope (Carlson et al., 1991). No discrete fan in the classical sense (e.g., Amazon Fan, Monterey Fan, etc.) occurs at the mouth of Zhemchug Canyon. It appears that the canyon was not an important source of sediment during the latest Quaternary because a subtle channel extends only a relatively short distance onto the deep Aleutian Basin of the Bering Sea.

“Swatch of No Ground” (Bengal Fan)

The Bengal Fan is the largest submarine fan in the modern ocean. Its length is at least 2800 km and its width locally exceeds 1400 km (Emmel and Curray, 1985). The apex of the

Bengal Fan is offshore of the “Swatch of No Ground” Canyon, which feeds the most recently active channel on the fan (Figs. 2 and 3). Unlike the Zhemchug Canyon, which has no associated major fan or fan channel, the Bengal Fan Channel fed by the incised Swatch of No Ground is an elevated levee-channel system. This elevated channel begins at 1400 m water depth on the continental slope and extends more than 2300 km down fan (Curray and Moore, 1974; Emmel and Curray, 1985). This contrast in canyon morphology is exemplified in the bathymetric contours of Figure 3, where the Zhemchug has a broad, flat floor at 3600 m water depth and extends into the basin as a broad, shallow depression in the seafloor.

The Swatch of No Ground is a delta-front canyon cut in flat-lying sediment of the shelf (Fig. 4B) and as such is probably a short-lived feature compared to submarine canyons cut in older sedimentary and basement rocks. As is typical for most modern canyons, the Swatch of No Ground, is inactive during the current high stand of sea level (Emmel and Curray, 1985). It is probable that the form and location of the Swatch of No Ground was different during previous periods of active sediment transport during glacial lowstands,reflecting changes inthe distributary system on the delta. Older equivalents of theSwatch of No Ground were probably similar in size or smallerbecause it is one of the larger delta front canyons in the modernocean,c.f.,Amazon and Indus (Fig.2).

Curray and Moore (1974) define the modern Bengal Fan toinclude the upper 4km of sediment under the fan apex. The volume of the Eocene to Holocene section under the Bengal Fan is 12.5 x 10^6 km^3 (Curray,1994). The volume of the Swatch of No Ground is 2.95 x 10^3 km^3 (Carlson and Karl,1988). Therefore, the amount of sediment that is Eocene and younger on the Bengal Fan is equivalent to a volume that is 4200 times the volume ofthe Swatch of No Ground itself. In contrast, the estimated vol-
ume of sediment in the Aleutian Basin of the Bering Sea is 1.9 x 10^6 km^3 (derived from Fig.4 in Cooper et al., 1987). If all of the sediment in the Aleutian Basin had been transported through the Zhemchug Canyon, it would equal only 325 times the volume of the canyon. Given that the enclosed Aleutian Basin (Fig.1) can

receive sediment from nearly all its margins, it is unlikely that the Zhemchug Canyon contributed more than a few percent of theequivalent volume that has passed through the “Swatch of NoGround” and its predecessors. Thus, it is clear that the smaller Swatch of No Ground has been a much more active funnel forbringing sediment to the ocean. The similarity of delta-fedcanyons in Figure2 suggests we can assume that ancestral canyons on the delta were roughly the same size.

OTHER LARGE SUBMARINE CANYONS AND TURBIDITE SYSTEMSIn this section, we look at examples of several other large submarine canyons and several additional large turbidite systems to emphasize the problems inherent in using canyon size to predict parameters for deposits that have formed on the seafloor as a result of processes within the canyons. We will start with other large canyons on the Beringian margin and then look at large turbidite systems, some of which are not associated with submarine canyons.

Bering Canyon and Fan

Bering Canyon is the longest of the Bering Sea canyons; it extends about 400 km across the Bering shelf and slope. It is confined at its eastern edge by the Aleutian Islands (Fig. 1). The width of the canyon at the shelf break is about 65 km, only about two-thirds that of the Zhemchug and Navarin Canyons (Fig. 2), but because of its great length, the Bering Canyon has the largest area (Table 1). At a depth of 3200 m, the Bering Canyon thalweg reaches the Aleutian Basin, where a low-relief submarine channel-lobe system has developed.

A fan channel extending basinward from Bering Canyon had been suggested on early bathymetric maps but was not clearly defined until the GLORIA survey (Bering Sea EEZ-SCAN, 1991). The fan channel extends several hundred kilometers into the Aleutian Basin as a low-relief (10–20 m), very broad (20 km), flat-floored turbidite channel (Figs. 5 and 6B). The Bering Channel has a low levee on its north side. The form of the channel is distinctly different from the elevated leveed channel systems found on large, delta-fed fans (Fig. 6A). The Bering Channel terminates in an area of very low-relief branching channels or channel remnants in a channel-lobe transition area (Figs. 5 and 6C;

Karl et al., 1996). Bering Fan lacks the distinctive upper, middle, and lower fan morphologic expression that is generally present on other fans (Karl et al., 1996); instead, it forms a relatively thin veneer of sediment in the Aleutian Basin. The turbidites fed by Bering Canyon underlie debris flow facies to the south and are indistinguishable from the Aleutian Basin fill in front of the Zhemchug Canyon. The latter observation also applies to the Aleutian Basin fill between Zhemchug Canyon and Navarin Canyon farther north.

Navarin Canyon

Navarin Canyon is the third largest submarine canyon that cuts the Beringian margin. It is the second largest in area, behind only the Bering Canyon, and its width at the shelf break is nearly the same as that of the Zhemchug Canyon (Fig. 2; Carlson and Karl, 1988). Navarin is also similar to the Zhemchug in that it has two main branches and it does not lead to any distinct submarine fan morphology. The lack of distinctive submarine fan morphologies for both the Zhemchug and Navarin Canyons, together with the very subdued relief of the Bering Fan, suggests that these canyons have not been particularly effective as major conduits for sediment transport from the continent.

The large canyons of the Beringian margin are not directly related to large rivers. During low stands of sea level, however, when the Alaskan shoreline was near the present 150-m isobath, the Yukon and Kuskokwim Rivers must have meandered across much of the emergent Bering shelf and, perhaps, influenced the development of the present-day heads of the Bering, Navarin, and Zhemchug Canyons. Today, the upper part of the Bering shelf valley can be traced to a position offshore of the Kuskowim River. Buried channels located in the outer shelf along the northern Bering margin suggest that streams that were, perhaps, ancestral to the present Yukon River must have meandered across the shelf, thus affecting the present day dual heads of Navarin and Zhemchug Canyons (Carlson and Karl, 1984).

Amazon Canyon and Fan

The Amazon Fan, which is one of the largest modern submarine fans (Bouma et al., 1985a), is one of the better documented submarine turbidite systems because of extensive mapping of the fan surface (Damuth and Flood, 1985; Pirmez and Flood, 1995) and the extensive scientific drilling during Ocean Drilling Program (ODP) Leg 155 (Flood et al., 1995, 1997; Normark et al., 1997). The canyon feeding the Amazon Fan is much less well documented. It is thought that the modern Amazon Canyon probably formed as a result of mass failures and then was modified by subsequent erosion by turbidity currents. The cross-sectional shape of the Amazon Canyon is similar to the other delta-fed canyon-fan systems, although it is smaller than either the "Swatch of No Ground" or "Swatch" Canyons (Fig. 2). The smaller size of the associated fan, however, has allowed for a more complete mapping of the surface morphology, and the Amazon Fan provides the best-documented examples of large, sinuous, leveed valleys that are common on delta-fed submarine fans (Fig. 6A).

The upper part of Amazon Fan comprises stacked channel-levee systems, which have a sinuous planform. The channel representation in Figure 7A gives the highly sinuous nature of the youngest leveed channel on the fan (Pirmez and Flood, 1995). The aggrading levees attain thicknesses of hundreds of meters in proximal parts of the fan and, as a result, both the channel floor and levee crest are elevated well above the surface of the adjacent fan (Fig. 6A). The highest rates of sedimentation on the Amazon Fan are on levee crests, locally as great as 25 m/k.y., and channel-floor deposits aggrade at rates in excess of 15 m/k.y. (Flood et al., 1997). The fan grew rapidly during Pleistocene low stands of sea level, accumulating some 500 m of sediment in the past 0.5 Ma. Channel width varies only slightly through time, as shown by the <2 km width of the high-amplitude reflectors under the channel floor (Fig. 6A). Thus, the sinuosity and position of the channel, which forms the conduit of an elevated 10–20-km-wide levee-channel system, appears to remain fairly constant during levee aggradation, and there is little evidence for significant lateral migration of meanders (Flood et al., 1997).

Major channels on the upper fan may persist for tens of thousands of years, with avulsion taking place more frequently on the middle fan and most commonly near the distal end of channels on the lower part of the middle fan (Pirmez and Flood, 1995). The sampling from ODP Leg 155 suggests that only one channel system is active at any given time. Avulsion apparently results from autocyclic controls and generally occurs as a result of either sediment failure on the levee or erosion by large turbidity currents.

Avulsion events do not appear to be controlled by sea-level change. Apparently, a single submarine canyon feeds the shifting channel system during each lowstand of sea level (Flood et al., 1995, 1997). Changes in the position of this feeding canyon during each lowstand produce a levee complex made up of a series of stacked channel-levee deposits. Successive levee complexes are separated by a thin layer of pelagic sediment that accumulates during sea-level highstand conditions (Flood et al., 1997; Normark et al., 1997).

Zaire Canyon and Fan

The Zaire Canyon, with its main fan-channel extension, was one of the first large modern canyon/fan systems to be described from the river source to the deep ocean basin (Heezen et al., 1964). The Zaire Canyon (Fig. 2) and Fan were originally called the Congo (Heezen et al., 1964), but recent workers use Zaire (Droz et al., 1996). The Zaire Canyon is somewhat unusual for a modern system in that the canyon head not only extends across the shelf (which in itself is uncommon during the present high stand of sea level); it also continues 30 km into the river estuary (Heezen et al., 1964). As a result, the canyon easily receives sediment from the river, and its current activity is attested to by frequent telecommunication cable breaks.

The canyon feeds a major fan valley system that is quite similar to those on the Amazon Fan. The channels are highly sinuous and have broad levees (Droz et al., 1996; Savoye et al., 2000). The channels can be traced about 900 km across the fan to the Angola Abyssal Plain. Droz et al. (1996) further observe that the Zaire Fan is unique in that it is a large turbidite system that remains active today under high stand conditions and because it is a large muddy turbidite system.

"Swatch" (Indus Fan)

The "Swatch" is the modern submarine canyon for the Indus Fan, which is the second largest turbidite system in the modern ocean (Bouma et al., 1985a). It is smaller than the Swatch of No Ground but has a similar shape (although narrower; Fig. 2) and relation to its fan (Kolla and Coumes, 1985). Similar to the other large, delta-fed fans such as the Amazon, the Indus Fan is characterized by large, leveed valley systems (Droz and Bellaiche, 1991). Long-range side-scan sonar images show that the leveed channel systems are sinuous and similar to the Amazon channels (Kenyon et al., 1995).

As noted for the Swatch of No Ground, the Swatch is a delta-front canyon that is probably a short-lived feature compared to submarine canyons cut in older sedimentary and basement rocks. McHargue (1991) mapped a series of leveed channels on the inner Indus Fan that were fed by a shelf canyon that was wider than the Swatch and lies about 100 km to the northwest.

Monterey Canyon

The Monterey Canyon has been one of the most studied modern submarine canyons since Shepard and Emery (1941); numerous workers have compared its width and depth to that of the Grand Canyon, e.g., Shepard (1963) and this paper, Figure 2. The Monterey Canyon is the largest and deepest of several canyons that lead to a 400-km-long submarine turbidite system called the Monterey Fan (Normark et al., 1985; Greene and Hicks, 1990). As a result of these multiple canyons feeding the fan, the history of development of leveed channel systems on the upper fan is relatively complex (Fildani et al., 1999).

Along its course to the fan, Monterey Canyon cuts through granitic basement and through Miocene and younger sedimentary rocks (Shepard and Dill, 1966; Greene and Hicks, 1990).

Early work concluded that the canyon is probably of Late Neogene age, and Greene and Hicks (1990) suggest that an ancestral Monterey Canyon originated by Early Miocene. Recent work on the age of sediment on Monterey Fan, however, indicates that the canyon, at least in its present form, may be no more than several million years old (Normark, 1999). Much of the older sediment underlying Monterey Fan apparently came from sources farther north than Monterey Bay (Fildani, 1993). In addition, the morphology of the largest leveed channel systems of the modern Monterey Fan show that they are probably not related to the current Monterey Canyon but to Ascension Canyon along the central California margin north of Monterey Bay. The main growth of the large leveed valley from the Ascension Canyon occurred in Late Pleistocene, and its present connection to the Monterey Canyon may have happened only within the last few hundred thousand years (Normark, 1999).

Horizon Channel

Horizon Channel extends nearly 1400 km southwest of Baranof Island, southeastern Alaska (Fig. 1). Figure 2 shows the cross section of this turbidite channel near the base of the continental slope. It is one of several very long channels in the Gulf of Alaska that feed the Tufts Abyssal Plain. Horizon Channel, with subparallel Mukluk Channel, are responsible for the major portion of the >200,000 km^3 of Late Miocene to Holocene sediment that has built the Baranof Fan complex (Stevenson and Embley, 1987). The ultimate sediment sources are the glaciated mountain ranges of southeastern Alaska and western Canada. At present, there is no submarine canyon that connects to the Horizon Channel. Rather, it is hypothesized (Stevenson and Embley, 1987) that as the Pacific Plate (Yakutat Block) moved northward, a series of small canyons and gulleys along the slope successively supplied sediment to the abyssal plain. In the process, three major fan channel systems were formed that presently make up most of the abyssal plain of the Gulf of Alaska, and none can be linked to prominent submarine canyons.

Laurentian Channel and Fan

The Laurentian Fan offshore eastern Canada is another example of a large turbidite system that is not fed by a prominent incised submarine canyon (Fig. 1; Piper et al., 1985). During low stands of sea level, sediment reached the fan through the Laurentian Channel, an 80-km-wide glacial trough that is incised 300 m deeper than the regional shelf depth; the shelf break at the end of the Laurentian Channel is about 400 m deep. The continental slope seaward of the Laurentian Channel is extensively gullied as a result of erosion of Late Quaternary sediment on the slope. The slope gullies transition downslope into several major fan valleys in water depths between 2000 m and 3000 m (see Fig. 2 in Piper and Normark, 1982). Two of these fan valleys extend for about 400 km to a low-relief sandy depositional lobe area, which extends another 400 km to the south (Piper et al., 1985). Turbidite sedimentation continues more than 500 km to the south beyond the fan margin onto the Sohm Abyssal Plain.

The Eastern Valley of Laurentian Fan, which is the largest of the fan channels on the upper fan, is also one of the largest turbidite channels yet documented. The Eastern Valley locally reaches a vertical relief of almost 1000 m from the channel floor to the crest of the eastern levee (Fig. 2). The valley floor adjacent to this area of high levee relief is nearly 20 km wide. Thus, in cross section, at its area of greatest relief, the Eastern Valley of Laurentian Fan is basically the same size as the Bering Canyon where it is measured at the shelf break (Fig. 2).

Although there is no major canyon associated with the fan, the Laurentian Channel was probably the main outlet for much of the ice in southern Quebec and the Atlantic Provinces of Canada during glacial periods. Similar to most modern submarine fans, the Laurentian Fan is basically inactive during the current high stand of sea level. The 1929 Grand Banks earthquake, however, generated a turbidity current event that disrupted telecommunication cables more than 500 km from the earthquake epicenter (see review in Heezen and Hollister, 1971). Sediment deposited from these turbidity currents has been recovered on the Sohm Abyssal Plain, indicating that the 1929 turbidity current flowed more than 800 km from the initiation zone near the earthquake epicenter. The flow was generated when the earthquake caused a series of mass failures on the upper slope in many of the gullies that feed into the channels on the Laurentian Fan (Normark and Piper, 1991). The volume of sediment carried in the 1929 Grand Banks turbidity current was about 160 km^3 (Piper and Aksu, 1987).

La Jolla Canyon and Fan

The La Jolla Canyon and Fan are included in this discussion to emphasize the physical-scale relationship between the biggest submarine canyons and turbidite fans and those canyons and fans that are more typical of those mapped in outcrop and borehole studies (Figs. 2 and 7). Large fans built on oceanic crust are rarely preserved in the rock record except as small, highly deformed slivers in subduction-zone complexes. The La Jolla Fan is one of several small turbidite systems off southern California that are contributing to the fill of San Diego Trough west of San Diego, California (Bachman and Graham, 1985). The La Jolla Canyon is the largest of these small systems (75 km2), but, like the others, sediment is supplied predominantly from beach sources and not by rivers. Until recently, the La Jolla Canyon was the best-documented submarine canyon for morphology, sediment distribution, and sedimentary processes (Shepard, 1963, 1973; Buffington, 1964; Shepard and Dill, 1966; Shepard et al., 1969; Bachman and Graham, 1985).

The La Jolla Fan is about 30 km in length from the head of the fan to the termination of the fan valley in San Diego Trough. A length of 20–50 km is typical for modern fans in basins of the California Borderland; e.g., the Navy Fan in South San Clemente Basin is about 30 km in length from its apex to the ponded basin plain, and Hueneme Fan in Santa Monica Basin is about 40 km long (Normark and Piper, 1985; Normark et al., 1998). Thus, analogs for understanding ancient turbidite systems are more likely to be based on La Jolla Canyon and fan sized-features than on the examples presented to define the world's largest systems.

DISCUSSION

The identification of the largest modern submarine canyon is straightforward if the criteria for selection are agreed upon, and Table 1 illustrates the choices available. The primary goal of this volume is to look at the largest sedimentary deposits that have formed in a variety of environmental settings and that represent a range of depositional processes. There is no simple relationship, however, between submarine canyon size and the size of the deposits that might be associated with these large canyons. For this reason, we chose to include a few smaller submarine canyons in our review to emphasize the physical scale range of submarine canyons that is involved as a backdrop for understanding a few observations concerning their deposits and, therefore, their legacy in the rock record. We do not attempt a comprehensive review; we have only selected a few examples to examine the differences between large canyons, large deposits of terrigenous sediment on the seafloor, and large depositional events.

Largest Canyon

The Zhemchug Canyon, which is the largest submarine canyon, is one of the best examples of a submarine canyon formed by repeated mass failures (Carlson and Karl, 1988; Karl et al., 1996). The volume of the Zhemchug Canyon is 5800 km^3; this is comparable to the largest submarine landslides that have been documented, e.g., the major collapses of the volcanoes of the Hawaiian Ridge, some of which exceed 5000 km^3 in volume and 200 km in length (Moore et al., 1994). Comparably sized landslides have been documented from continental margins as well, e.g., the Storrega slide on the Norwegian margin, which exceeds 5500 km^3 (Kenyon, 1987).

The Beringian continental margin, which is underlain by an outer shelf structural high, is incised by three humungous submarine canyons. The present morphology of these canyons is primarily the product of mass sediment failures (Carlson, Karl, and Edwards, 1991). Where the Beringian margin now exists, the Pacific (Kula) plate was possibly subducted beneath the North American plate, according to Scholl et al. (1975), contributing to weakness and resulting in subsequent canyon erosion of the margin. This subduction, together with subsequent Cenozoic glaciation, may have influenced the development of the large canyons (Karl et al., 1996). Buried canyons and channels suggest intermittent channel development as the Beringian margin evolved during the Cenozoic. For example, the shelf landward of the margin contains evidence of buried channels that crossed the shelf from rivers such as the Yukon and Kuskokwim, The shelf then may have been destabilized by earthquakes and or large storm waves, for which the Bering Sea is famous, and moved downslope as large slump or slide blocks, mass flows, or turbidity currents, continuing to incise the canyons into the Beringian continental slope.

Large Canyons and the Rock Record

The relationship between size of modern canyons and the size of their associated deposits is illustrated in Table 2. The examples selected are ranked (from large to small) by area of the canyon within two groups: those cut into the continental margin and those that are on river deltas. As noted earlier, the largest canyons, all from the Beringian margin, are incising the edge of the continent. Table 2 includes an estimate of the area of the submarine fan and associated turbidite and mass-transport deposits that have been fed by the canyon. The ratio of the deposit area to the canyon area is also shown, from which it is clear that the bedrock-cutting canyons have much smaller deposit areas than do the generally smaller canyons formed on major deltas. The ratios for bedrock canyons are less than 100 while the ratios for the largest fans range from about 150 to nearly 650. If the Laurentian Fan, which does not have a canyon but multiple slope gullies, is excluded, then the difference in ratios between the two groups is more pronounced.

As a check on this general relationship, we compare two small, well-studied turbidite systems from offshore California formed in tectonically active inner basins of the California Borderland. The La Jolla and Hueneme Canyons are similar in size, but the ratio of the canyon to deposit area of the delta-fed Hueneme Fan and basin plain is twice the area of the La Jolla deposits (Table 2), despite the fact that the Hueneme Fan is in a completely enclosed basin.

Except for canyons that feed sediment to basins formed on continental crust, the submarine canyons themselves have a better chance of surviving in the rock record than do the deposits they feed (Normark et al., 1993). Much of the record of submarine fan deposition on the deep ocean floor is eventually lost when the oceanic crust on which submarine fans are formed is ultimately subducted. In general, only small remnants of these deep water systems are incorporated into the continent. The canyons, which are cut in the continental margin or formed on delta fronts, may be preserved, but—especially in the case of the bedrock-eroded canyons—not necessarily with sediment fill that is representative of their primary activity as a conduit for terrigenous sediment to reach the seafloor. Submarine canyons that have been preserved in the rock record are generally small in area (500 km2 to 2000 km2) and typically are filled with mudstone underlain by minor amounts of coarser-grained facies (see comparisons in Williams et al., 1998). Of the modern examples presented herein, it is the smaller systems formed in basins on continental crust, e.g., the Hueneme and La Jolla systems, that are likely to remain as part of the rock record (Normark et al., 1993).

Submarine fans fed by large rivers—e.g., Bengal, Amazon, Indus, etc.—have broad, leveed-channel systems. The levee sequences appear relatively acoustically transparent on seismic-reflection profiles and are assumed to be generally muddy. Scientific drilling on the Mississippi and Amazon Fans has confirmed the muddy nature of these levees (Bouma et al., 1985b, 1985c; Flood et al., 1995, 1997). As a result, these large, delta-fed fan systems have become known as muddy turbidite systems. Drilling away from the levees on these muddy fans, however, has shown that sand is a major component of much of the rest of the fan and is not that different from supposedly sand-rich systems fed by canyons cut in continental margins (see review in Piper and Normark, 2001).

Large Depositional Events

As already noted in the discussion on Laurentian Fan Valley, large turbidity current events are not necessarily related to the largest canyons. One of the largest turbidite deposits documented in the modern ocean was generated by the catastrophic floods resulting from the rapid draining of glacial Lake Missoula. The floodwaters kept flowing as a hyperpycnally generated turbidity upon reaching the ocean at the mouth of the Columbia River (Zuffa et al., 2000). The turbidity current initially moved through Astoria Canyon, which is only 2000 km2 in drainage area and 425 km^3 in volume (Carlson and Karl, 1988). Part of the deposit from the floods was trapped in the Escanaba Trough nearly 1000 km from the river mouth and was cored during ODP Leg 169. Using the data from Zuffa et al. (2000), it can be shown that the largest turbidite bed left by the flood-generated turbidity currents exceeded 80 km^3. In total, there are about 175 km^3 of Missoula flood sediment in Escanaba Trough. These authors also showed that it is unlikely that Escanaba Trough contains more than a few percent of the total sediment transported. Thus, it appears that the volume of sediment in the largest turbidity current generated by the Missoula floods is an order of magnitude larger than the volume of the canyon. This suggests that the flows generated by glacial-lake floods may have taken many days to transit through the canyon and/or overwhelmed the canyon and flowed down the adjacent continental slope as well.

Many of the submarine canyons discussed here are formed to a lesser or greater extent by mass failures. The extent of mass failures for the largest canyons are on the order of the largest slumps and debris avalanches found on continental margins and oceanic volcanoes.

CONCLUSIONS

The task of determining the largest submarine canyon in the world is difficult because one must decide which physical parameter—length, relief of incision, cross-sectional area, or volume—is the most important criterion. Ultimately, we have discovered that no single canyon leads the candidates in all four categories; however, the Bering Sea margin has been sculpted by three canyons that are collectively the leaders in all four physical parameters. Zhemchug Canyon has the greatest relief (2600 m, measured at the shelf break) and the largest volume, 5800 km^3 and is our choice as the largest modern canyon. Zhemchug and Navarin Canyons share the honors of being the widest at the shelf break (~100 km). Bering Canyon is the longest, stretching 400 km, with the greatest area of incision (30,000 km2) from shelf to abyssal plain.

By contrast, the largest submarine fans—Bengal, Indus, and Amazon—are all fed by small canyons incised into their respective deltas that are generally an order of magnitude smaller than those cut in older sediment or basement. The rivers that feed these largest fans are all associated with significant mountain ranges, the Himalayas and Andes, which provide substantial sediment to the rivers. In general, the deposits related to delta-front canyons are much more extensive than those related to canyons that incise the bedrock of continental margins (Table 2).

Despite the extensive area of the seafloor covered by sediment that has been transported through the larger canyons and the delta-front troughs off the larger rivers, in the end, it is the deposits of small submarine canyons and fans formed on continental crust that have the greatest potential for being preserved in the rock record.

ACKNOWLEDGMENTS

We hope that in writing this review paper, we have correctly acknowledged and properly used the many references required. It came clear in reviewing the literature on submarine canyons that we, as well as all fans of submarine canyons, owe a debt to Francis P. Shepard. The paper has been improved by reviews from H. A. Karl,S. L. Eittreim, D. R. Lowe, and G. Shanmugam.

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Figures and Tables

Table 1. Area of submarine canyons.

TABLE 1. AREA OF SUBMARINE CANYONS

No.	Canyon	Area (km^2)	Comments	Reference
1	Zhemchug	11,350	Largest cross section (Fig. 2) and largest volume of incision on continental margin but only third in total area (see Fig. 6).	Carlson and Karl (1988)
2	Bering	30,800	Longest canyon (495 km); only large Beringian margin canyon that has associated submarine fan	Carlson and Karl (1988)
3	Navarin	14,600	Second largest in area (Fig. 6) and in volume of incision on continental margin	Carlson and Karl (1988)
4	Monterey	2380	Cross section at shelf edge is greater than Grand Canyon width and relief (Fig. 2)	Normark et al. (1985)
5	La Jolla	33	Size is typical of canyons that provide sediment to continental margin basins that are analogs for many hydrocarbon resource areas	Buffington (1964); Shepard and Dill (1966)
6	Horizon Channel	n.a.	The channel, which is more than 1200 km long, is not connected to a submarine canyon but to slope gullies, possibly associated with glacial trough	Stevenson and Embley (1987)
7	Swatch of No Ground	9000	Current (modern) canyon for Bengal Fan, the world's largest fan with channels extending more than 2000 km (Fig. 6)	Shepard (1973); Smith and Sandwell (1997)
8	Swatch	1700	Current (modern) canyon for the Indus Fan	Shepard and Dill (1966)
9	Amazon	2250	Current (modern) canyon associated with the river having largest discharge	Damuth and Kumar (1975); Milliman (1979); Damuth and Flood (1985)
10	Zaire (Congo)	4470	Canyon extends 30 km into the Zaire River Estuary and feeds a fan nearly 1000 km in length	Heezen et al. (1964); Droz et al. (1996)
11	Laurentian Fan Valley	n.a.	Largest levee/channel floor relief (Fig. 2); the fan valley heads in a gullied upper slope below the mouth of a glacial trough cut 300 m below the shelf	Piper and Normark (1982); Piper et al. (1985)

Note: Numbers refer to map in Figure 1. Area given represents total submarine drainage area of canyon and tributaries. If canyon area is not provided directly by the reference(s) listed, it is derived from maps presented in these references.

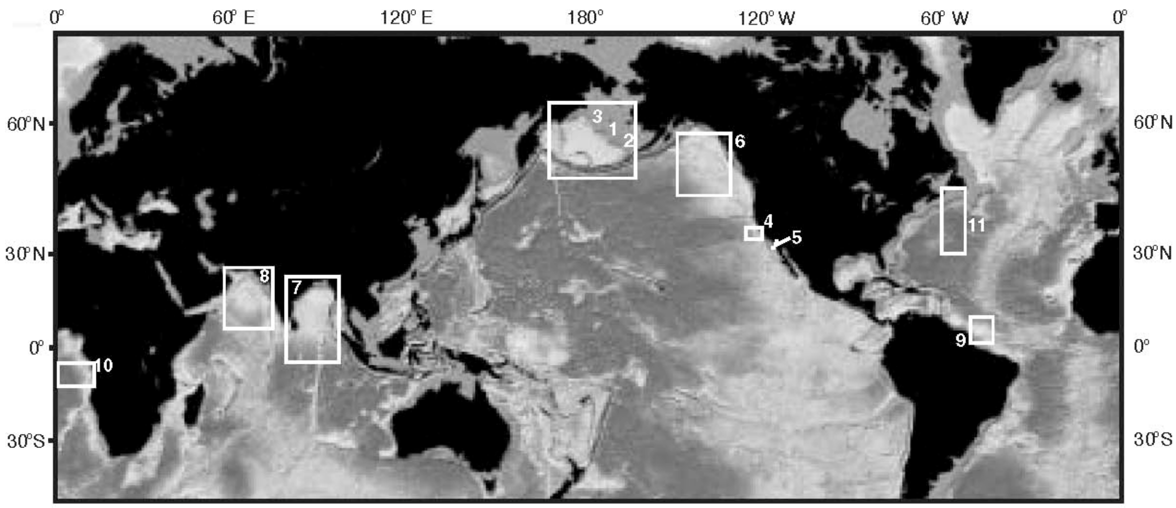

Figure 1. Shaded world relief map with locations of submarine canyons and associated turbidite deposits mentioned in text (shaded relief from Miller et al., 2001). Canyon-fan systems are: (1) Zhemchug, (2) Bering, (3) Navarin, (4) Monterey, (5) La Jolla, (6) Horizon Channel (leading to Tufts Abyssal Plain in Gulf of Alaska), (7) Swatch of No Ground (Bengal), (8) The Swatch (Indus), (9) Amazon, (10) Zaire (Congo), and (11) Laurentian Fan Valley and Sohm Abyssal Plain. At this "world view" scale, only three large submarine canyons can be distinguished on Bering Sea margin. Light shading in boxes denoting canyon-fan systems generally marks areas covered by turbiditic fan deposits. Several larger submarine fan channels are shown for scale comparison. See text for discussion and references.

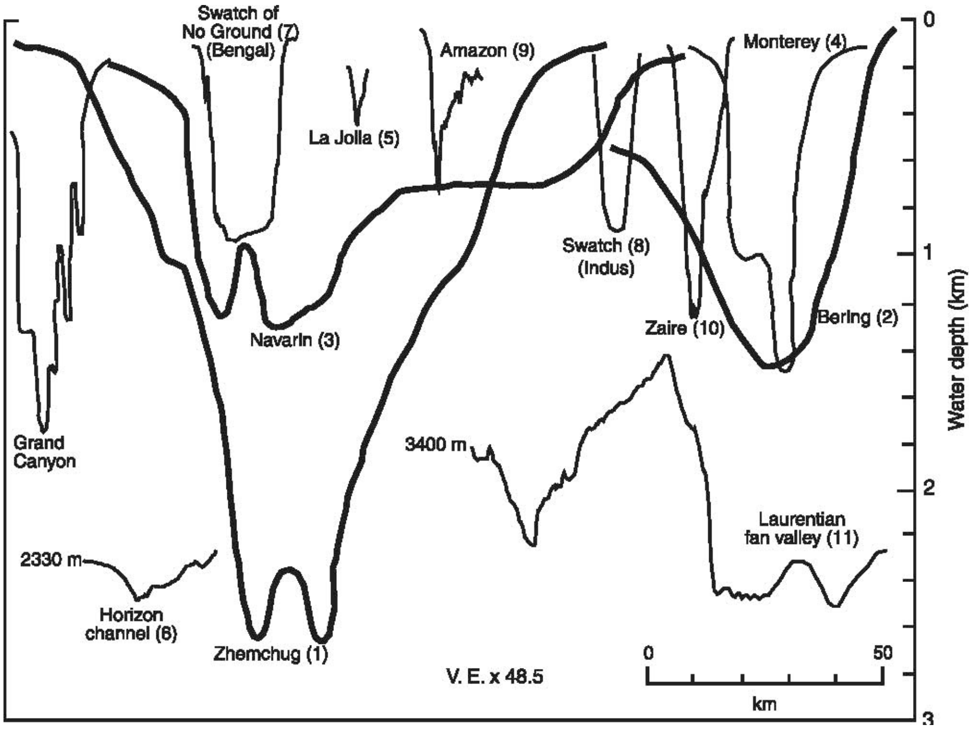

Figure 2. Comparison of canyon cross-sections near shelf edge for selected fans shown in Figure 1 and Table 1. Canyon sections are plotted at true depth; Horizon and Laurentian turbidite channels are plotted at same scale and water depth is given at left side of profile. Sections for three largest canyons are shown with bold lines. Sections for Bering, Monterey, Navarin , and Zhemchug submarine canyons and Grand Canyon are from Carlson and Karl (1988). Sections for other submarine canyons and fan channels are: Amazon Canyon (Damuth and Kumar, 1975); Horizon channel (Stevenson and Embley, 1987);
La Jolla Canyon (Shepard and Buffington, 1968); Laurentian fan valley (Piper and Normark, 1982);
Swatch (Shepard, 1973); Swatch of No Ground (Curray and Moore, 1974; Shepard, 1973); Zaire (formerly
Congo, Heezen et al., 1964).

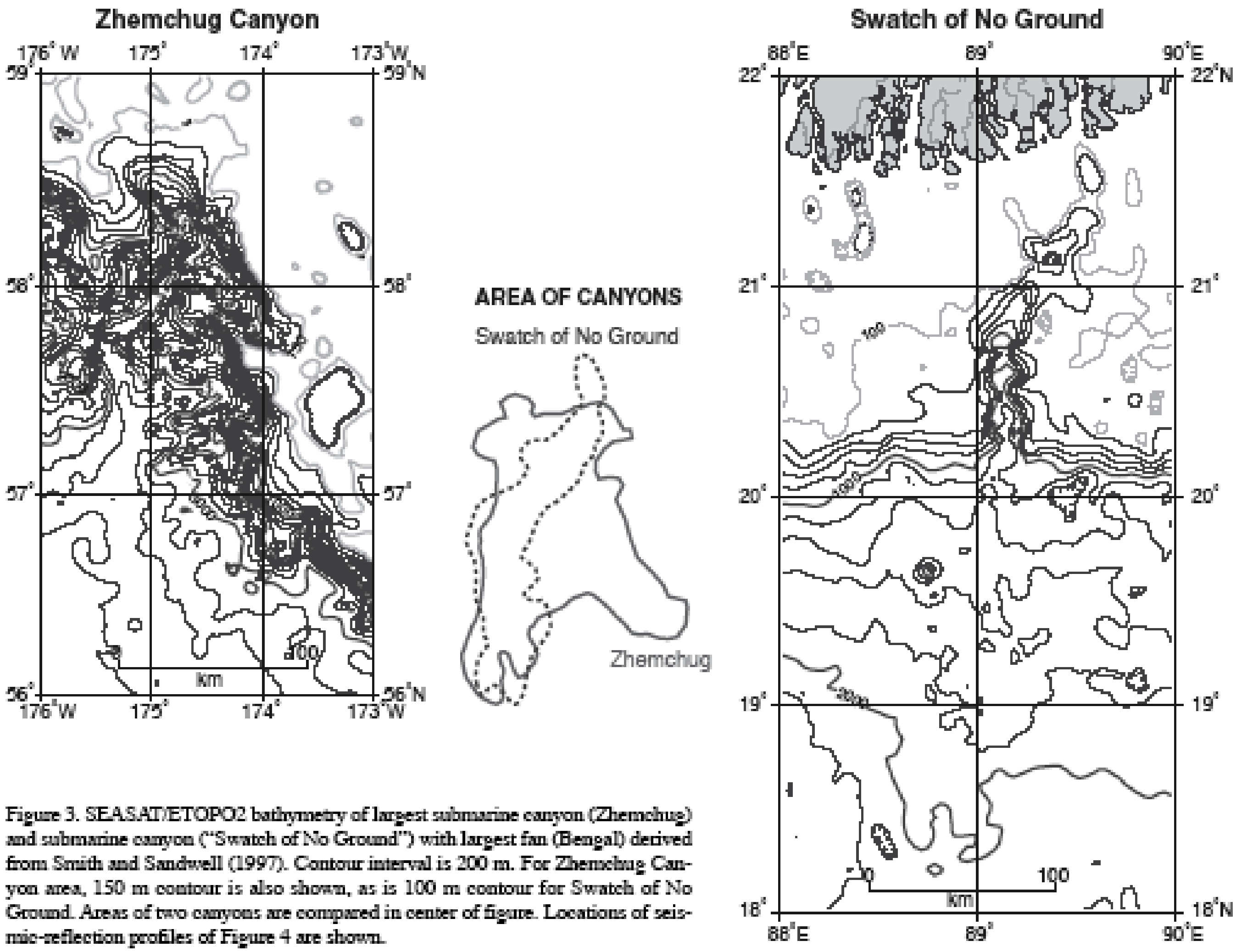

Figure 3. SEASAT/ETOPO2 bathymetry of largest submarine canyon (Zhemchug) and submarine canyon ("Swatch of No Ground") with largest fan (Bengal) derived from Smith and Sandwell (1997). Contour interval is 200 m. For Zhemchug Canyon area, 150 m contour is also shown, as is 100 m contour for Swatch of No Ground. Areas of two canyons are compared in center of figure. Locations of seismic-reflection profiles of Figure 4 are shown.

Figure 3. SEASAT/ETOPO2 bathymetry of largest submarine canyon (Zhemchug) and submarine canyon ("Swatch of No Ground") with largest fan (Bengal) derived from Smith and Sandwell (1997). Contour interval is 200 m. For Zhemchug Canyon area, 150 m contour is also shown, as is 100 m contour for Swatch of No Ground. Areas of two canyons are compared in center of figure. Locations of seismic-
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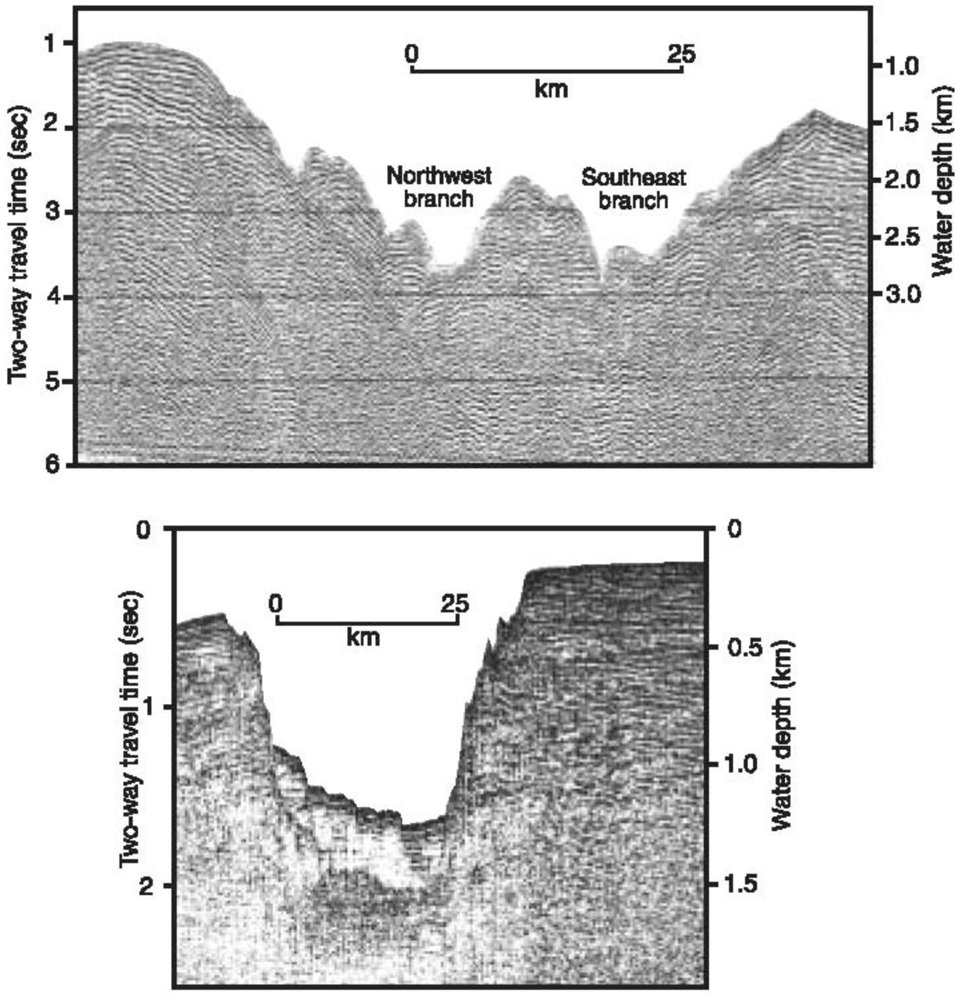

Figure 4. Seismic-reflection profiles across Zhemchug and Swatch of No Ground canyons. (A) Airgun seismic-reflection profile crossing rugged, slump-dominated walls of Zhemchug Canyon. This profile crosses two branches of this massive canyon slightly east of shelf edge. Profile collected on cruise F-3-86-BS (Bering Sea EEZ-Scan Scientific Staff, 1991). (B) Profile across Swatch of No Ground showing thick fill and/or slump deposits in canyon floor (adapted from Shepard; Fig. 11–21 in Shepard, 1973). See Figure 3 for location.

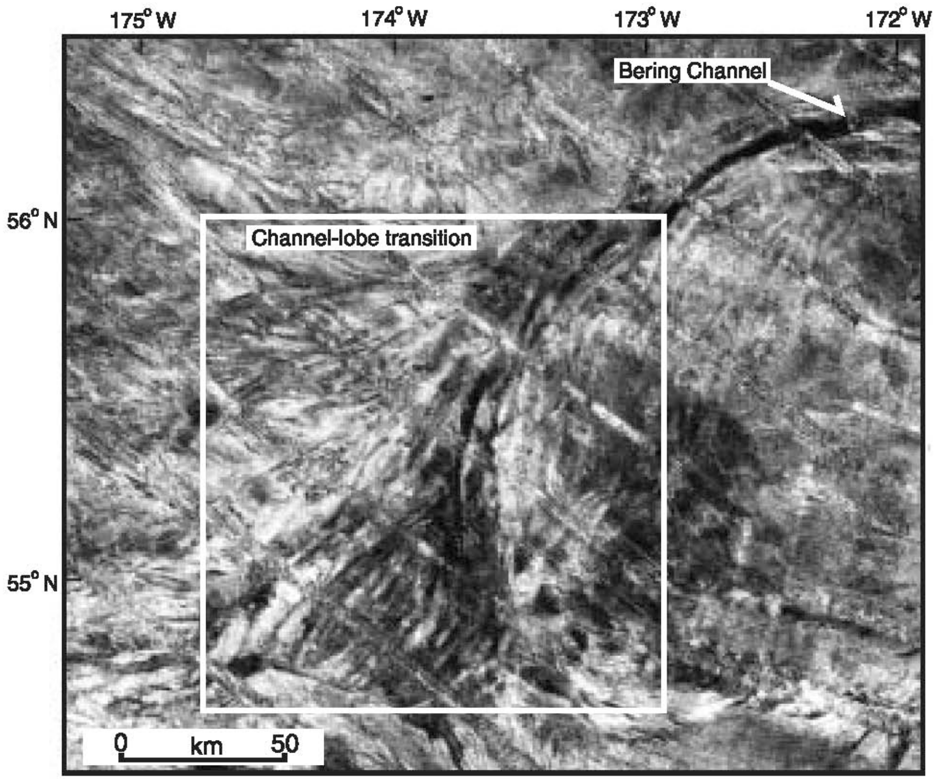

Figure 5. Long-range side-scan sonar image of area of channel-lobe transition seaward of Bering Channel from GLORIA survey of Aleutian Basin (adapted from Fig. 17-6 in Karl et al., 1996).

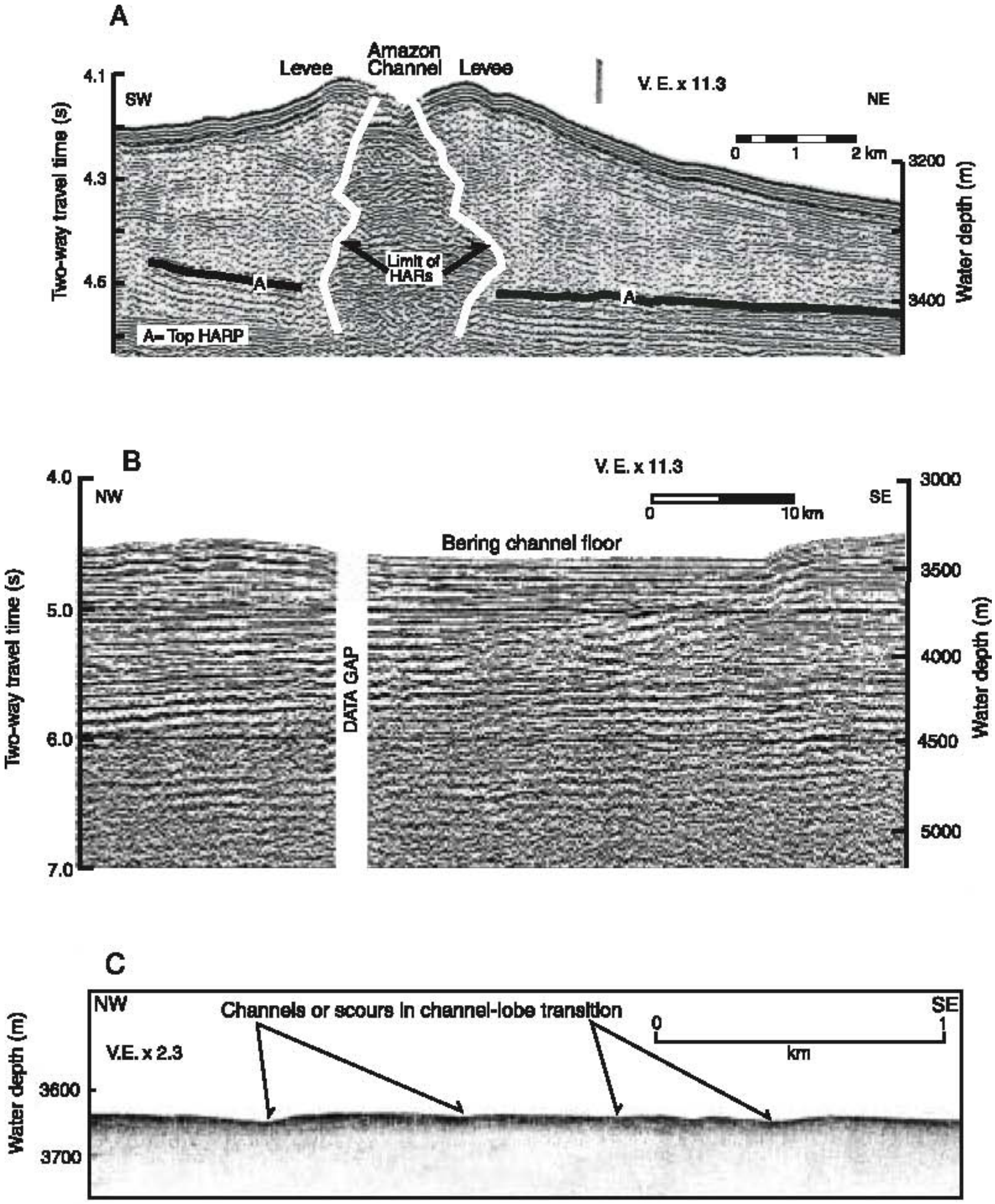

Figure 6. Comparison of submarine fan channels. A: Leveed channel typical of large, delta-fed submarine fans (modified from Flood et al., 1995). Leveed-channel complex overlies High Amplitude Reflection Packet (HARP), denoted A. Wide levees are deposited on low-relief, gently sloping HARP contact, where channel floor was initially incised before aggradation of entire levee-channel complex. B: Seismic-reflection profile across Bering Fan Channel just upstream (east) from channel shown in northeast corner of Figure 5. C: Small Bering Fan channels

resolvable in 3.5-kHz profiles across low-relief, channel-lobe transition (adapted from Fig. 17-14 in Karl et al., 1996).

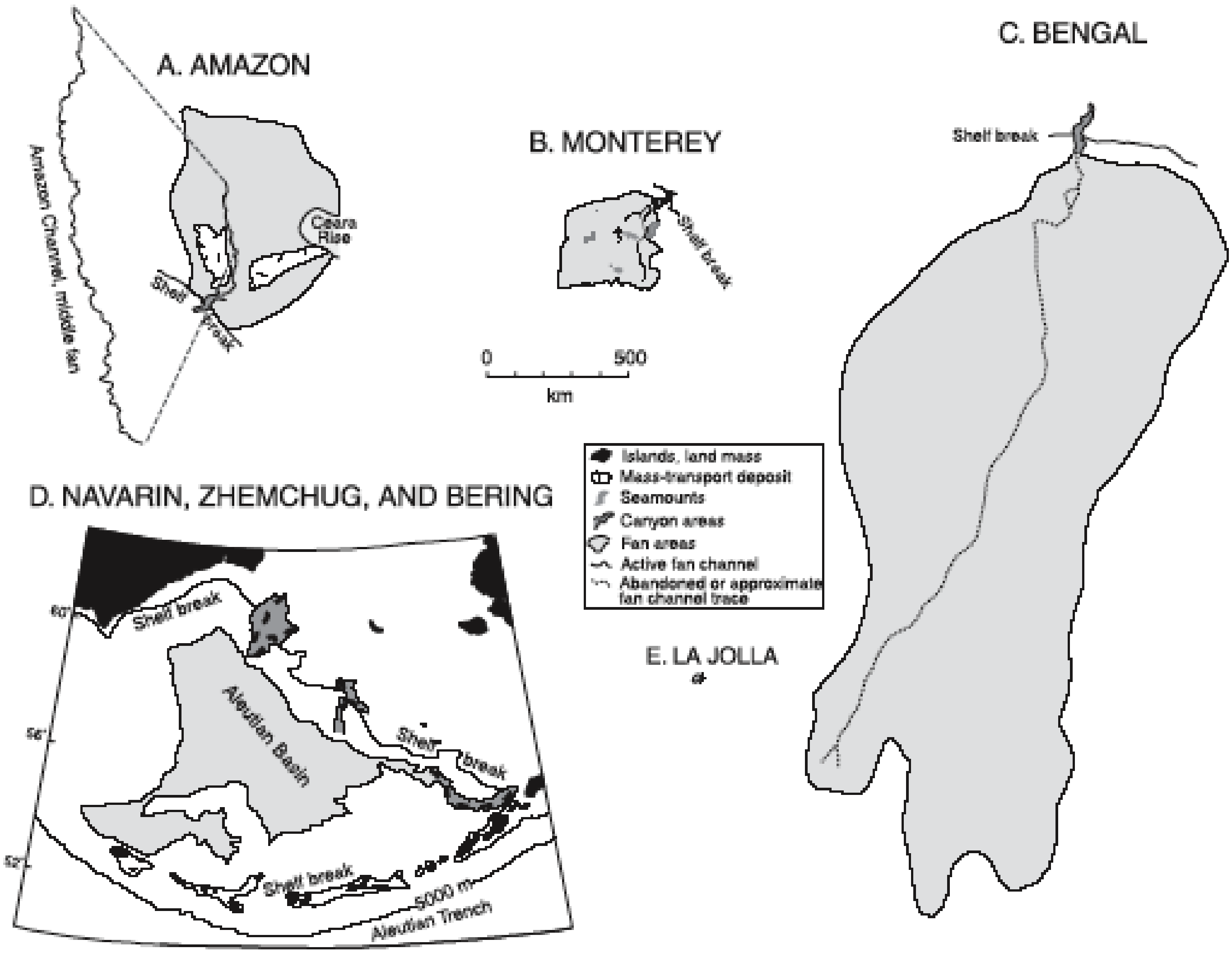

Figure 7. Comparison of submarine canyon area and area of related submarine fan. Examples are constructed using the following references:
(A) Amazon Canyon Fan (Milliman, 1979; Damuth and Flood, 1985); sinuous Amazon Channel on middle fan is shown in blowup to left (Pirmez and Flood, 1995); (B) Monterey Canyon Fan (Normark et al., 1985; Fildani et al., 1999); (C) “Swatch of No Ground” and Bengal Fan (Shepard, 1973; Emmel and Curray, 1985; Smith and Sandwell, 1997); (D) Zhemchug, Navarin, and Bering Canyons and Aleutian Basin (Carlson and Karl, 1988; Karl et al., 1996); (E) La Jolla Canyon and Fan (adapted from Moore, 1972).

Table 2. Comparison of the areas of canyon and of their deposits.

TABLE 2. COMPARISON OF THE AREAS OF CANYONS AND OF THEIR DEPOSITS

Canyon/Fan (if not same name)	Canyon area (km^2)	Depositional area (km^2)	Area ratio	References*
Incised margin canyons				
Bering	30,800	190,000	6	Carlson and Karl (1988); Karl et al. (1996)
Navarin	14,600	~250,000	17	Carlson and Karl (1988); Karl et al. (1996)
Zhemchug	11,350	~250,000	22	Carlson and Karl (1988); Karl et al. (1996)
Zaire (Congo)	4470	330,000	74	Heezen et al. (1964); Droz et al. (1996); Savoye et al. (2000)
Laurentian Fan Valley †	3800	375,000	99	Piper and Normark (1982); Piper et al. (1985)
Monterey	2380	95,600	40	Normark et al. (1985); Fildani et al. (1999); or Reid et al. (1999)?
La Jolla	33	880	27	Buffington (1964); Shepard and Dill (1966)
Delta-front canyons				
Swatch of No Ground/Bengal	9000	2,040,000	227	Shepard (1973); Smith and Sandwell (1997);
Amazon	2250	330,000	147	Damuth and Kumar (1975); Milliman (1979); Damuth and Flood (1985)
Swatch/Indus	1700	1,100,000	647	Shepard and Dill (1966); Kolla and Coumes (1985)
Hueneme	25	1400	56	This study based on Normark et al. (1998)

Note: Canyon Area refers to the submarine-drainage footprint of the canyon (from Table 1). Depositional Area includes mass-wasted deposits, turbidite fans, and any associated basin plain or abyssal plain (where these latter elements have been distinguished by previous work).

* Interpretation of the canyon and fan areas is based on data provided in the references listed for cases where that value was not provided in references directly.

† Interpretation of the Laurentian "canyon" area is based on the sum of the areas of the multiple slope gullies that lead to the main leveed valleys on the fan.